The Cellular Automatiste

ABOUT THIS ISSUE. . .

— Rollo Silver

This is the first issue of *The Cellular Automatiste*: the newsletter for people who are inordinately fond of Cellular Automata. Its subject matter will be dictated more by your interests, dear reader, than by mine. I hope that much of the material will be contributed by you.

This issue features two articles. The first is "Conway's *Life* (Part 1)" by Harold McIntosh. John Horton Conway's game of *Life* was the quintessential introduction to cellular automata for most of us. McIntosh's article, an excellent introduction to that fascinating game, explores many of its features.

Many investigators have succeeded in applying cellular automata theory to problems in physics and chemistry in the form of "programmable matter". Rudy Rucker's article, "A Survey Of Some Zhabotinsky-style Two-dimensional Cellular Automata", investigates how well certain CAs unveil the mystery of the chemical effect known as the Belousov-Zhabotinsky reaction.

CONWAY'S *LIFE* (Part 1)

— Harold V. McIntosh

1. Introduction

The game of *Life* is an invention of John Horton Conway, a British mathematician. It was widely publicized in the early seventies through Martin Gardner's monthly column "Mathematical Recreations" in *Scientific American*. Programmers at numerous computer centers set out to explore the game with the machines at their disposal, those with access to visual display equipment having somewhat of an advantage, particularly if their equipment was interactive. Nevertheless many others apparently found pencil and paper adequate to obtain significant results.

Sufficient interest existed to maintain a quarterly newsletter, which was published by Robert T. Wainwright, for almost three years. The third issue was certainly one of the highlights of the series, reporting a wide variety of constructions, of glider guns, glider collisions, puffer trains and so on. A sufficient number of artifacts were found to enable Conway to demonstrate a universal constructor, which has been one of the principal goals of the theory ever since John von Neumann became interested in automatic factories.

The factories which he envisioned don't just make particular things; they work from a description of whatever they are supposed to build. Presumably one of them could be given its own description, making it universal in accordance with Alan Turing's sense of the theory of computability.

Gradually computer capacity and the theoretical understanding of the subject became saturated, although there were attempts in later years to apply some of the precepts of information theory to the game. A new surge of interest was provoked from another direction when detailed computer experiments with nonlinear differential equations

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began to illuminate some of the more abstruse theories of topological dynamics. Quite independently of the fact that cellular automata define the continuous mappings within one esoteric approach to the subject, Stephen Wolfram thought that he saw an application of Stephen Smale's theory of strange attractors to one dimensional cellular automata. He created a classification into four categories for the occasion.

The early eighties saw intensive activity on Wolfram's part, exploring the evolution of linear cellular automata of one kind or another, with the intention of relating their behavior to the theory of computational complexity as well as the topologists' classification of the asymptotic behavior of dynamical systems. Some insights that were gained from this approach, such as the use of de Bruijn diagrams to discover the periods of cycles of evolution, can be applied to the original game of *Life*, and so resolve some of the questions which were left unanswered during the original excitement.

It is also true that the computers with which *Life* can be studied have improved over the years, both in terms of capacity and of availability. Results which were previously out of reach can now be computed, with the prospect of obtaining still further results as the performance of computers improves. Nevertheless one of the lessons to be learned is the exponential growth of all such computations; what can be calculated will always remain relatively modest.

Attempts to modify Conway's rule have not met with much success, although variants have been considered. The apparent 2^{2^9} different choices of a rule is illusory; rules without rotational and reflective symmetry are not acceptable, nor are rules without a quiescent state. Given restrictions such as totality, thousands or millions of candidates remain — many, but not entirely impossible, to sort through.

Some promising three dimensional analogues of *Life* have been found, but working with higher dimensions is clearly a formidable proposition.

2. The Rules of the Game

Automata are characterized by having states, and rules for deciding whether and how to change their states from time to time. The cells making up cellular automata all change their own states simultaneously, according to the states of their neighbors in the lattice in which they are situated. Consequently a cellular automaton is classified by the basic number of states its cells can display, and the exact form of its neighborhood.

With just two states per cell, binary automata are simplest. The distinction between "living" and "dead" or "inactive" gave the published version of *Life* a readily understandable ecological interpretation, then a very popular concern.

As for their neighborhoods, the first consideration is *dimension* and the second *radius*. One dimensional automata are very restricted in the way that connections can eventually be established between the cells; perhaps a reason that they were generally disregarded before Wolfram's interest. Two dimensional automata are more satisfactory, although von Neumann had to exercise considerable ingenuity to be able to construct crossing wires which would not short circuit each other. Two dimensional automata seem to suffice; more dimensions would increase the complexity of all computations without necessarily providing any better insight, granted that the conclusions to be drawn from them are highly symbolic anyway.

Even though a two dimensional network has been chosen, there are choices among square, triangular and hexagonal lattices, as well as the exact constitution of the neighborhood. Von Neumann used a square lattice, taking single neighbors on each side in both the horizontal and the vertical direction, but he needed a large number of states to accomplish his purpose (28 plus a quiescent state). Conway settled for fuller neighborhoods, restricted to binary cells. Thus *Life* uses diagonal neighbors as well as lateral neighbors; a neighborhood contains altogether nine cells, eight of them bordering the central cell.

Finally, the rule of evolution has to be chosen. Conway's final choice was

- A live cell survives if it has two or three live neighbors;
- A new cell is born whenever there are three live neighbors;
- All other cells either die or remain inactive.

Fanciful interpretations assuming some strange kind of microbe provide a useful metaphor for discussing the game, but are not to be taken too seriously.

Conway's criterion was that the rule should neither lead to populations which quickly die out, or which expand without end from limited beginnings. Through Martin Gardner, he challenged the readers of *Scientific American* to find out whether long term growth was nevertheless possible. Two mechanisms were suggested.

The first was by the construction of a "glider gun". Early experimentation with the rule had revealed an aggregate of five cells which moved across the *Life* field in a diagonal direction, advancing one square every four generations. If some mass of live cells could be found which emitted gliders periodically, it would produce the growth he was seeking. Evidence for the existence of some such configuration was the fact that gliders were frequent evolutionary products in random fields that had been observed. William Gosper at MIT soon found one glider gun; then another, structurally different one, was found. Since then no more have been reported.

The second possibility was that there were more complicated objects than gliders which could also move about a *Life* field leaving stable debris behind. Belief in their existence was encouraged by the fact that certain larger structures, which were christened "space ships", had been found, which moved horizontally or vertically, and that numerous small stable structures had been observed in the evolution of random fields.

Interestingly enough, a variety of "puffer trains" were also found, but more interesting still was the discovery that there were puffer trains that left gliders as debris in just such a fashion that they could collide to form glider guns.

This last combination, a mass whose periphery increases linearly with time, violated Conway's concept of a stable ecology in the worst possible way; nevertheless it was a carefully engineered and delicate construct, and not a combination likely to be found by chance. The behavior of the rules which he had discarded was evidently much cruder.

3. Still Lifes

Since all finite automata eventually evolve into a cycle of states which repeat indefinitely thereafter, cycles are one of the first things to look for; the same principle holds for infinite automata as well, even though such repetition is not obligatory. The shortest possible cycle, with period 1, would be a configuration of states which never changes; they are called *still lifes.*

A field in which all cells are inactive remains so; such quiescence was deliberately included in the definition of *Life.* Examination of the evolution of random *Life* fields reveals many still lifes formed from small clusters of live cells; the simplest is a 2 x 2 square: each cell has exactly three neighbors, and so persists from one generation to the next. Cells outside the cluster have at most two live neighbors, which is never enough for any additional cells to be formed. Thus the conditions for a still life are met.

An empirical search of random fields reveals configurations that are easily formed, especially if a very limited sample is taken. It needs to be supplemented by a more thorough procedure, so it is not surprising that much of the response to Gardner's article consisted in carefully recording the evolution of all the small objects that it is possible to form. Gradually a catalog was built up of still lifes of up to twelve pixels, including several families of still lifes and rules for generating them.

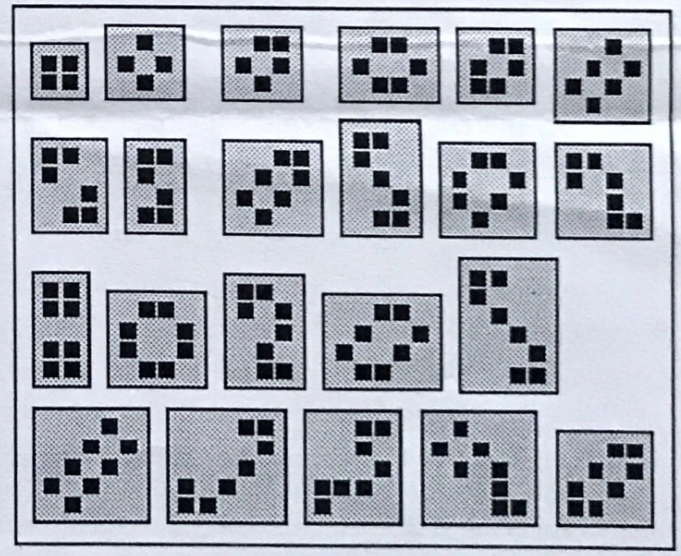

Figure 1: some small still lifes

Figure 1 shows the 22 symmetry classes of connected still lifes containing eight live cells or less. The symmetry of *Life's* evolutionary rule ensures that objects differing by rotation or reflection undergo a similarly rotated or reflected evolution, so only one representative of each class has to be shown.

4. Period Two

The structures called *blinkers*, consisting of three live cells in a row, alternate in form between three horizontal cells and three vertical cells:

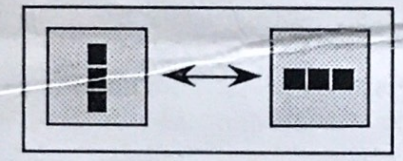

Figure 2: blinker

Next to square clusters of four blocks, they are the most common debris remaining after evolution has run its course. They exemplify structures with period two, which like the smaller still lifes, often arise during the evolution of random fields.

Alternators, or period two oscillators, tend to be rather fragile. Nevertheless, they are easily constructed, once the basic technique has been grasped. There are really two different kinds of alternators, depending on whether cells disappear from isolation or from overcrowding.

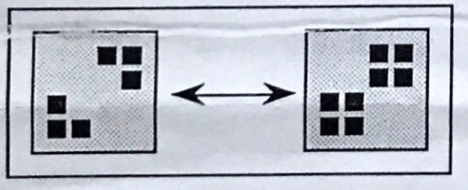

Figure 3: simple overcrowding alternator

Of course, it is possible for a large configuration to incorporate both kinds of alternators.

Figure 4 shows an assortment of alternators which depend on overcrowding.

The neighbors of the deceased remain in place, giving birth to a new cell which they promptly crush, repeating the cycle indefinitely. The cells colored black persist in both halves of the cycle. Those colored grey alternate in the two halves with those colored white.

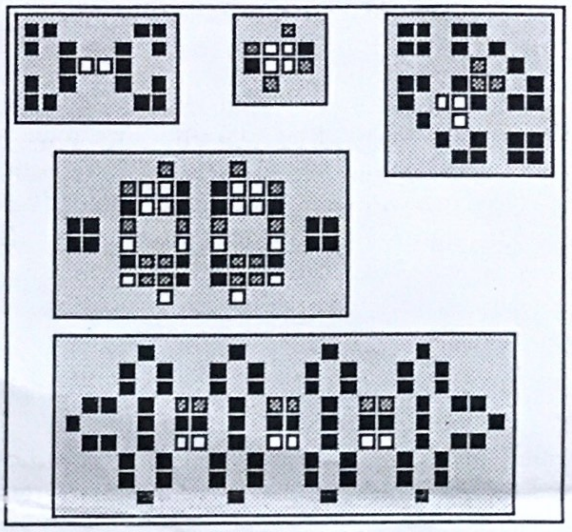

Figure 4: overcrowding alternators

5. Gliders

Gliders were probably the most unexpected characteristic of Conway's *Life*, and in the end the one responsible for its great complexity and utility. Conway quickly realized that gliders were the substitute for von Neumann's wires as the mechanism for transporting information from one place to another in the *Life* field. They form an essential ingredient of his demonstration of a self-replicating configuration for *Life*, which doesn't detract from their interest for other applications.

Figure 5: glider evolution

Figure 5 shows the four phases of a glider, which would constitute a cycle except for the displacement. The glider evolves through four forms, each having five cells. The fifth form is the same as the first, except for having moved one square southeast. Because of the displacement, gliders can never have a finite period in an infinite *Life* field; an exception to the theorem that finite automata must eventually retrace a cycle of states, except for the finiteness condition. Allowed to evolve on a finite torus, a glider will have a period sufficiently long for it to traverse the length of the torus and return to its starting position.

A variety of glider precursors were reported in Wainwright's newsletter; in view of the asymmetry

of the glider itself, it would seem that the principal requirement for the precursor is that it — or significant segments of it — also be asymmetric. For all of their interest and importance, gliders are not hard to find in random *Life* fields. It is reported that they were first observed wiggling their way across a video display. Their prevalence is consistent with the fact that they are formed from only five live cells, since the smaller stable figures are by far the most common residues of long term evolution.

The search for other moving configurations eventually turned up the three space ships shown in Figure 6.

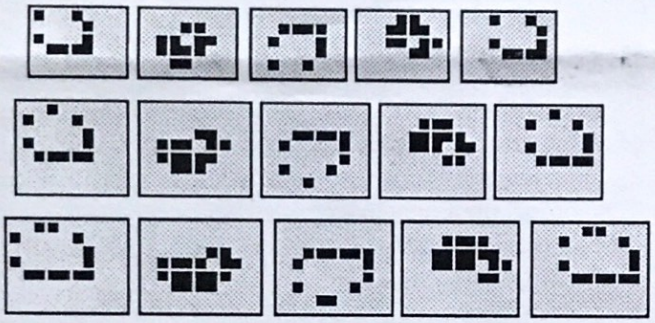

Figure 6: The three primitive space ships

They and their symmetric images are capable of horizontal or vertical motion.

Certain other combinations produce the puffer trains which Conway had foreseen. However, gliders and the three small space ships are the only primitive structures that have ever been found capable of self propulsion.

6. Oscillators

Compared with the ease with which still lifes or alternators can be formed, it is quite difficult to form configurations with longer periods, so that they are not often found as transients during the evolution of random fields nor among the debris which remains when they have stabilized. Nevertheless their construction is not impossible, and oscillators of every small period have been found. As with alternators, they tend to fall into different categories depending upon the mechanism involved.

One scheme is to create vacancies and then replacements for them, a common aspect of the two classes of alternators. If the replacement can be deferred, a longer cycle than that of period two can be created. Figure 8 shows a cycle of length three created in this manner.

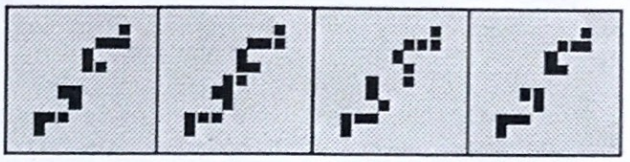

Figure 7: A period three oscillator

Another mechanism is to note that some configurations are naturally expansive, such as those which evolve from a long row of live cells.

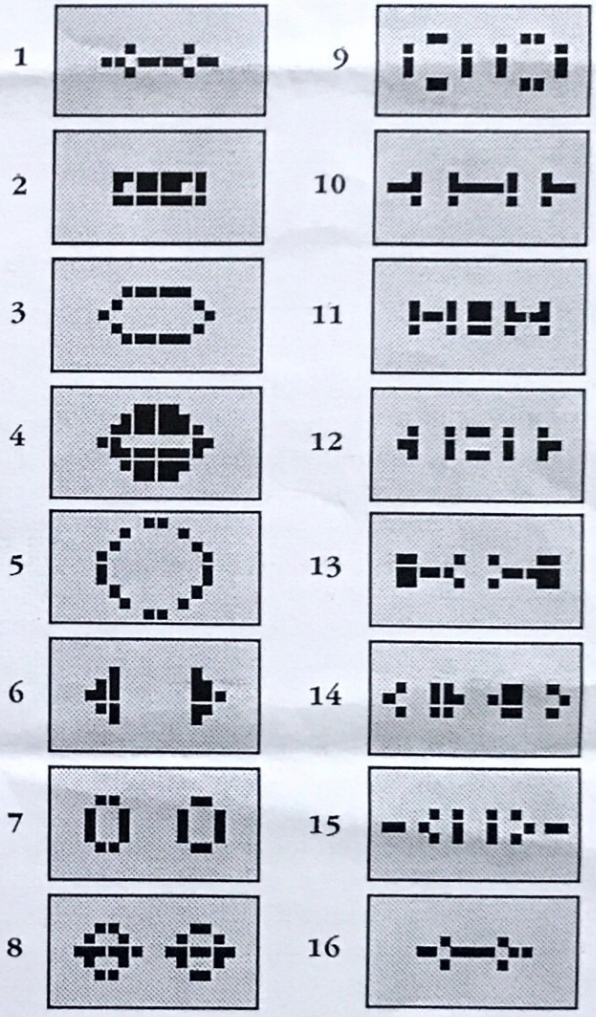

Figure 8: A period fifteen oscillator based on expansion and contraction

However, as the center of the row expands laterally the end of the row contracts longitudinally; the competition between these two tendencies can result in an alternation which leads to a cycle of

long period. Experimentation when *Life* was still new led to the discovery that a row of ten live cells, slightly modified, would reproduce itself after fifteen generations, as shown in Figure 8 (previous page).

Another configuration which behaves similarly is formed by two solid 3 x 3 squares staggered diagonally, touching at their corners (Figure 9).

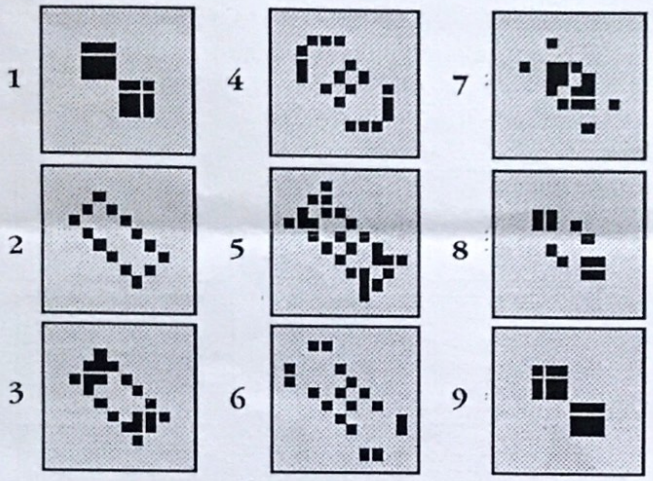

Figure 9: A period eight oscillator based on two squares

Yet another arrangement which can be exploited for arbitrarily large assemblages of live cells is to surround figures which are known to be highly expansive with other figures, highly stable, which are known to dampen expansion. Under favorable circumstances the central figures will reconstitute themselves from the debris, phoenix like, to initiate a new cycle. By repeating itself periodically the combination becomes an oscillator whose period depends roughly on the distance from the center to the periphery.

Many experiments have been performed to observe collisions of moving objects with each other, with still lifes, or with oscillators. Collisions between a glider and the period fifteen oscillator have been studied in detail. Most collisions are messy, but there are some where the glider will simply be eaten, having struck inessential trash in the oscillator.

For just one arrangement, the glider reflects. Thus a composite oscillator with an arbitrarily long period can be constructed by bouncing a glider back and forth between two oscillators.

There are even rare collisions which turn the glider by 90° rather than 180°.

(To be continued)

A SURVEY OF SOME ZHABOTINSKY-STYLE TWO-DIMENSIONAL CELLULAR AUTOMATA

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INTRODUCTION

Most cellular automata (CAs) seem to meet one of four fates: they die out, they start repeating themselves, they turn into structureless seething, or they break up into gliders which bounce off each other forever. But there is a fifth option: the Zhabotinsky-style CA reaction.

In the two-dimensional Zhabotinsky-style CAs I have studied, characteristic double-scroll patterns are formed. The scrolls organize themselves from seeds found at random in the starting pattern. Existing scrolls spin off small child-scrolls that resemble small vortices spawned by large vortices. The boundaries between competing scrolls' terrains are fluid and under constant revision.

The name *Zhabotinsky* comes from A.M. Zhabotinsky who, with his colleagues at the Institute of Biological Physics near Moscow, carried out extensive investigations of a double-scroll chemical reaction that was discovered by B.P. Belousov in 1958 [Win74]. The CA rules I discuss here have a qualitative resemblance to the chemical Zhabotinsky reactions, but they do not necessarily have any close connection with the details of the chemical process.

As the designer of a two-dimensional CA simulation package [Ruc89$_2$], I have spent an inordinate amount of time looking at various kinds of two-dimensional CAs. In the course of my quest for interesting and beautiful rules, I have been struck by the number of different CA contexts in which Zhabotinsky-style rules arise. I now feel that Zhabotinsky-style rules are a broad and important

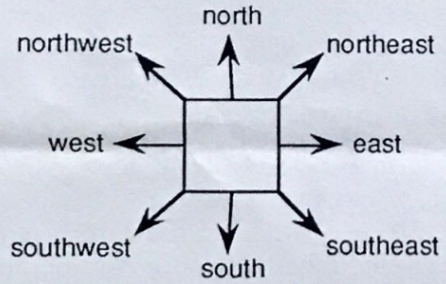
class of CA. In this paper, I will describe four different families of Zhabotinsky-style rules: *NLUKY, Hodge, Eat, and Tube*. The *NLUKY* rules are my own discovery. The *Hodge* rules were discovered by Martin Gerhardt and Heike Schuster. See [Dew88], and the refinement of this rule discussed in [Ger90]. The *Eat* rules come from David Griffeath and Bob Fisch. See [Gri88] and [Dew89]. The *Tube* rules come from Norman Margolus and Tommaso Toffoli [Mar87].

TERMINOLOGY

All the CAs to be discussed use a two-dimensional square grid of 320 by 200 cells. The same sorts of patterns arise regardless of whether one allows the screen to wrap around. Given an arbitrary cell, let C be the positive integer representing the cell's state, and let the new value of the cell which the CA rule calculates be called *NewC*.

With the exception of the *Eat* rules, in the rules to be discussed *NewC* depends on two things: the cell's value C and the value of the sum of the cell's neighbors. Rules of this sort are called "semitotalistic" by Stephen Wolfram [Wol86].

As is customary, we think of the cell as having eight neighbors: the northwest, north, northeast, west, east, southwest, south, and southeast neighbors. I will be interested in two different ways of



summing up a cell's neighbors' values to get numbers which I call *FullEightSum* and *FiringEightSum*.

FullEightSum is simply the sum of the eight neighbor states. If the highest usable state number is, say, N, then *FullEightSum* will be a number between 0 and $8N$. We also define *FullEightAverage* as *FullEightSum*/8.

The idea in forming *FiringEightSum* is that a cell's state can be thought of as a binary number, and we can give special significance to certain bit positions. *FiringEightSum* focuses on each state's lowest bit. If a neighbor cell's low bit is 1, it contributes 1 to *FiringEightSum*, otherwise it contributes 0. *FiringEightSum*, in other words, is the sum of the lowest bits of the eight neighbor states. *FiringEightSum* will always be a number between 0 and 8.

NLUKY RULES

An *NLUKY* rule is specified by five positive integer parameters: N, L, U, K, and Y. N can be arbitrarily large; the other numbers can range from 0 to 9. Actually these numbers could range from 0 to 8; the value 9 is simply used as a signal that a certain possibility is being excluded. The *NLUKY* rule is specified as follows:

(N1) The cells have $N+2$ possible states: 0, 1, and the N even numbers $2, 4, 6, \ldots, 2N$.

(N2) If $C = 0$ and $L \le FiringEightSum \le U$ then $NewC = 1$;
If $C = 0$ and not$(L \le FiringEightSum \le U)$ then $NewC = 0$.

(N3) If $C = 1$ and $K \le FiringEightSum \le Y$ then $NewC = 1$;
If $C = 1$ and not$(K \le FiringEightSum \le Y)$ then $NewC = 0$.

(N4) If $2 \le C < 2N$ then $NewC = C+2$

(N5) If $C = 2N$ then $NewC = 0$.

The state 0 is called the *dead* state, state 1 the *firing* state, and states $2, 4, 6, \ldots, 2N$ are called the *refractory* states. The well-known *Game of Life* rule is the *NLUKY* rule 03323. Brian Silverman's *Brain* rule is the *NLUKY* rule 12299. My motive for inventing the *NLUKY* categorization was in fact to find a common setting for these two rules. See [Ruc89] for a discussion of a different way of combining these two rules.

Life, on the one hand, seems to gain much of its power from the fact that a firing can sometimes keep firing. *Brain*, on the other hand, gets its richness from the fact that it has a refractory or resting state. Arbitrary *NLUKY* rules can have both these features.

On of my biggest surprises came when I found that many of the *NLUKY* rules are in fact Zhabotinsky-style rules. The simplest example is *NLUKY* rule 72322, which I call *RainZha*. In practice it seems that almost any rule of the form *N2U2Y* produces a Zhabotinsky pattern, so long as *U* is greater than 3.

The *NLUKY* rule N2222, which I call *Faders*, is not a Zhabotinsky-style pattern, but what it does is unique: the pattern grows firing gliders, which come in either a right-handed or a left-handed form. As a right-handed glider moves along it shoots right-handed gliders out to its right, cumulatively leading to fractal patterns that attempt to become spiral, with right-handed gliders which send out right-handed gliders, which themselves send out right-handed gliders, etc. Spirals cease developing when a glider's great-grandchildren run into its trail.

HODGE RULES

The *Hodge* rules are formulated in terms of two positive integer parameters, N and I. N can be arbitrarily large, and I should be less than N. Typically, a value of I approximately equal to $N/6$ works well. The rule is specified in terms of *FullEightAverage* (= *FullEightSum*/8). In the following, $\lfloor I/2 \rfloor$ is the greatest integer not exceeding $I/2$.

(H1) The cells have $N+1$ possible states: 0, 1, 2, ..., N.

(H2) If $C = 0$ and $FullEightAverage = 0$ then
$NewC = 0$;
If $C = 0$ and $0 < FullEightAverage \leq I$ then
$NewC = \lfloor I/2 \rfloor + 1$;
If $C = 0$ and $I < FullEightAverage \leq 2I$ then
$NewC = I$;
If $C = 0$ and $2I < FullEightAverage$ then
$NewC = \lfloor I/2 \rfloor + 1$.

(H3) If $0 < C < N$ then
$NewC = FullEightAverage + I$, unless
$FullEightAverage + I > N$, in which case
$NewC = N$

(H4) If $C = N$ then $NewC = 0$.

The details of part (H2) of the definition are unimportant; many different ways of passing from state 0 to a nonzero state seem to work here. Note that the *Hodge* rules are closely related to the simple *Rug* rule in which
$NewC = (FullEightAverage + I) \bmod N$.
The crucial difference between *Hodge* and *Rug* is that when a *Hodge* cell value gets larger than N, it is set back to N, and then in the next cycle to 0, whereas in a *Rug* rule a cell value larger than N is wrapped around to the amount by which N is exceeded. No double-scrolls ever arise in *Rug* rules.

EAT RULES

The *Eat* rules are formulated in terms of a single integer parameter N, which can be arbitrarily large. There are two kinds of *Eat* rules: the *deterministic* and the *non-deterministic*. The non-deterministic version requires the use of a randomizer to select repeatedly one of a cell's neighbors.

(E1) The cells have N possible states:
0, 1, 2, ..., $N-1$.

(ED2) (Deterministic 2) If any of my cell's neighbors has state $(C+1)$ MOD N, then
$NewC = (C+1)$ MOD N, otherwise
$NewC = C$.

(END2) (Non-Deterministic 2) If my cell's randomly selected neighbor has state
$(C+1)$ MOD N, then
$NewC = (C+1)$ MOD N, otherwise
$NewC = C$.

The deterministic *Eat* rules quickly converge to tight small spirals that are somewhat monotonous to look at. The non-deterministic rules are more exciting, although the higher the N-value, the large will be the size of the cell grid required for the rule to get started from a uniform random initial condition. With my grid of 320 x 200, a value of $N = 12$ is about the largest for which action spontaneously develops. One can, however, force action out of a rule with a large N value in various ways. One trick is to randomize the screen, and then set a disk or patch of cells to state 0. For $N = 16$ a zero patch of size 8 x 8 will suffice.

TUBE RULES

The *Tube* rules are specified in terms of four positive integer parameters: *Fuzz*, *A*, *O*, and *E*. *A* specifies a threshold value, *O* is the number of odd states, and *E* is the number of even states. We require that $O \geq 2$ and $E \geq 1$. *Fuzz* is either 0 or 1. The rules are formulated in terms of a boolean *SafeCondition*:

SafeCondition $\leftrightarrow$ *FiringEightSum* $< A$ or (*Fuzz* = 1 and *FiringEightSum* = $A+1$).

The *Tube* rules can now be specified as follows:

(T1) The cells have $O+E+2$ possible states: 1, 3, ..., $2O-1$ and 0, 2, 4, ..., E.

(T2) If $C = 1$ and *SafeCondition* then $NewC = 1$; if $C = 1$ and not(*SafeCondition*) then $NewC = 3$.

(T3) If C is odd and $1 < C < 2O-1$ then $NewC = C+2$.

(T4) If $C = 2O-1$ then $NewC = 0$.

(T5) If C is even and $0 \leq C < 2E$ then $NewC = C+2$.

(T6) If $C = 2E$ and *SafeCondition* then $NewC = 1$.

(T7) if $C = 2E$ and not(*SafeCondition*) then $NewC = 3$.

Margolus and Toffoli discuss three variations on this rule. The first two variations take *Fuzz* to be 0 and set *AOE* to 234 and 334. Their third variation takes *AOE* to be 334, but changes *Fuzz* to 1. The first of the three reactions converges rapidly to small square spirals, the second converges more slowly to rounded octagonal spirals, and the third rule (which appears on the cover of [Mar87] makes very nicely rounded fuzzy spirals. In general, if *A* is 2 or 3 and *E* is either $O+1$ or $O+2$, these rules will produce Zhabotinsky-style patterns.

GENERAL COMMENTS

The main things which all these rules have in common is (1) the existence of a cyclic sequence of states which the cells can move through, and (2) a mechanism which can tend to bring the states of nearby cells into synchronization. The sources of synchronization are as follows:

In the *NLUKY* rules a firing cell urges neighboring cells to fire. In the *Hodge* rule, cell states sit and wait for their fellows for one cycle each time they shoot past the maximum value. In the *Eat* rules, certain values get copied into their neighbors. And in the *Tube* rules, a state 1 cell can wait until more than *A* of its neighbors enter odd states.

Why do the Zhabotinsky-style rules form double scrolls? A double scroll is really a line segment which is radiating a stimulation out of one of the line's sides. The stimulation is more intense at the line's interior points, so the central part of the scroll emanates there. At the line's ends the stimulation falls off, so the stimulation dies down and gets rounded off in a spiral.

I would like to see some Zhabotinsky-style CAs in which the two ends of the side-pulsing lines are dissimilar. The purpose of this would be to break the approximate bilateral symmetry of the double-scrolls, producing patterns closer to paisley than to involute leaves or Ionic column capitals.

Taxonomic and aesthetic considerations aside, Zhabotinsky-style rules are very important for the development of CA-based artificial life. In Zhabotinsky rules we have large, self-maintaining structures which grow out of random soup, just as one would like artificial life to do. It is very striking how strongly the Zhabotinsky double-scrolls resemble fetuses. If a two-dimensional Zhabotinsky-style CA produces lines which wrap around themselves, three-dimensional CAs of this class should produce planes which wrap around themselves producing shapes like mushrooms and possibly like nautilus shells as well. One three-dimensional analog of the double scroll is two nautilus shells glued lip to lip — very fetus-like indeed. What a fascinating laboratory of mathematical life the Zhabotinsky-style CAs may lead to!

SOFTWARE

These rules can be easily viewed with the general purpose PC cellular automata simulator *CA Lab* [Ruc89$_2$]. A new product, *James Gleick's Chaos: The Software* [Gle90] includes a special "Toy Uni-

verses" model which I wrote specifically to show the rules discussed in this article.

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If you submit something for publication in xx, please include a brief biographical sketch, if you don't mind. I suspect that our readers would like to know something about you!

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